A remote sensing observatory for hydrologic sciences: A genesis for scaling to continental hydrology

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[1] Uncertainties in assessing the effects of global-scale perturbations on the climate system arise primarily from an inadequate understanding of the hydrological cycle: on land, in oceans, and in the atmosphere and biosphere. Because of this uncertainty, almost all science-based initiatives have expressed the need for continued advances in global observations and modeling of the Earth system. It is in this spirit that we advocate establishing a hydrologic remote sensing observatory (RSO) to advance sensing technologies and their use in scientific inquiry into hydrologic processes. There are two fundamental reasons why establishing such a RSO is timely. The first is operational: Developing assimilation techniques to estimate unobserved fluxes and uncertainties in hydrologic forecasts has sufficiently matured to take advantage of computing facilities and detailed hydrologic observations shaped by the RSO. The second is scientific: This RSO will permit us to refine knowledge from physical and hydrologic models that can then be converted to local and global strategies for water resources management and ecosystem health evaluation. The authors outline the conceptual design, scope, and functionality of a RSO and present four examples to illustrate how the hydrologic community can take advantage of such facility.

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1. Introduction and Problem Statement

[2] The complexity and heterogeneity of hydrologic interactions exists over a wide range of scales in space and time. It is also widely accepted that remote sensing, broadly defined as a collection of noncontact observational methods, offers the potential to capture some of the intricacies of these spatial and temporal processes. Yet, hydrology today finds itself in a paradigm lock with respect to understanding the controls on hydrologic fluxes and states and how these controls vary spatially and temporally with scale and how the land surface and subsurface couples with the overlying atmospheric boundary layer. The current paradigm is that a given hydrological scale, whether it be a "Darcian," catchment, or the atmospheric boundary layer, the nonlinear dynamics describing water transport is presented as a function of the state at that resolved scale, and all finer scale (or faster) processes are treated as subgrid. Much coarser scale processes are generally assumed to be either sufficiently slow, or their effects are prescribed as forcing. It is clear then that the high dimensionality of hydrologic processes prohibits us from tracking cross-scale interactions across space and time. This knowledge gap invites the use of multiscale data offered by remote sensing platforms; however, the remote sensing algorithms are insufficiently developed for these complex processes to provide the spatial observations necessary for exploring cross-scale information flow.

[3] To break this lock we propose establishing an integrated remote sensing observatory (RSO) where research across the spectrum of hydrologic remote sensing can be integrated with hydrologic processes occurring at scales of less than a meter to thousands of kilometers. Historically, remote sensing products have been evaluated through short-term activities focusing on a single geophysical variable. We question this approach, and instead offer a vision of a community observatory where fundamental research on the estimation of water-energy-ecosystem variables can be carried out in an integrated manner across complex landscapes. The observatory offers the potential of improved predictions from remote sensing measurements for other

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regions, thus offering the hope that remote sensing can be used to address fundamental hydrologic research questions at local to global scales. These are the issues of critical importance to international activities such as the World Climate Research Programme's Global Energy and Water Cycle Experiment (GEWEX), the Prediction in Ungauged Basins (PUB) [*Sivapalan et al.*, 2003], and the United States Global Change Research Program's Water Cycle Initiative.

[4] This opinion paper is developed around our belief that understanding terrestrial hydrologic processes across scales must include remote sensing measurements at multiple scales, and that the proper use of the data requires, as a logical first step, research into the statistical and physical relationships among remote sensing measurements, in situ measurements, and hydrologic modeling. Existence of a long-term observatory would allow effective pursuit of these goals and efficient use of collective resources and efforts. We envision a "prototype" of such an observatory to be a piece of land that is well instrumented with in situ and ground-based high-resolution remote sensing instruments that allow detailed observations of the hydrologic processes occurring at the site. In that respect the embryonic form of the RSO would be similar to an extended field experiment such as those conducted in the past, with the main difference being the duration and comprehensiveness of instrumentation and variables measured. Careful definition of control volumes and nested sampling schemes would facilitate resolving the terms of the energy and water balances with known errors and providing observations for investigations of scaling relationships.

[5] Recurrence of major field experiments, such as the recent Soil Moisture–Atmosphere Coupling Experiment (SMACEX [*Kustas et al.*, 2005]) and NASA's Ground Validation programs for precipitation, are all indications that the concept of a RSO is sound. Below, we offer a sample set of examples appropriate for such an observatory, and sketch out how the observatory would foster the research. We also show that the proposed observatory is consistent with the scope of the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) HydroView research infrastructure.

[6] While it is clear that over the last decade, satellites have proven the capability to monitor many aspects of the total Earth system on a global scale, it is also clear that aircraft- and ground-based systems play a vital role in improving our understanding of hydrologic processes and their interactions. Thus the first step in constructing the skeleton of such a RSO is to use well-established methods that have a proven success record such as weather radar, lidar, as well as radiometers and spectrometers. The main hydrologic variables of interest include precipitation (especially liquid), snow water equivalent, evapotranspiration, surface water reservoirs and river discharge, soil moisture, precipitation interception, groundwater storage, soil freezing and thawing, and ecosystem variables like vegetation biomass and carbon content.

2. Science and Research Questions and Issues

[7] We argue that the hydrologic research community needs a remote sensing observatory to address numerous science questions that range from the spatial-temporal dynamics of hydrologic processes across complex landscapes to the statistical properties of hydrologic variables retrieved via remote sensing and their assimilation into hydrologic models. Below we offer four examples that in our opinion are representative of important hydrologic research problems to which remote sensing can contribute and for which an observatory is the appropriate mechanism for answering the questions.

4. Closing Remarks

[56] The concept of the remote sensing observatory we propose should be viewed as development of new capabilities and not as a large-scale experiment. For remote sensing to be useful in studies at hydrologic observatories as well as in monitoring continental and global-scale water resources, it needs to be investigated through a series of focused studies. A number of questions and issues remain; we have discussed some of them in this paper. We need a statistical approach to test for consistency between remote sensing and ground data. We need to quantify uncertainty in derived remote sensing products and ground measurements. We need to improve our understanding of subgrid heterogeneity and its effects on hydrologic processes. We need to develop approaches to assimilate remote sensing data and products into new models and theories.

[57] At remote sensing observatories many variables would be monitored at comparable scales. The necessity of this multicomponent approach has been recognized by those currently involved in remote sensing validation efforts. For example, the SMEX 2002 experiment in Iowa has demonstrated the value of boundary layer and water vapor monitoring for interpretation of passive microwave remote sensing of soil moisture. Even in validation of precipitation (seemingly an external input) the information on three-dimensional wind structure, atmospheric stability and humidity of the prestorm and poststorm environment are critical for proper interpretation of the results.

[58] How should we go about establishing RSOs? While the developing structure of the CUAHSI seems well suited for the task, it is still somewhat of a moving target. Therefore we resist temptation of putting our RSO concept into the framework of CUAHSI. Our main objective in this paper was proposing a concept, not a design. We hope this paper will stimulate the hydrologic community to initiate more discussion on the issues and needs we raise herein. As the scope of remote sensing is wide, developing smaller focused prototypes of RSOs may be a good first step to consider. In designing such prototypes we should capitalize on lessons learned from previous community experiments such as FIFE, BOREAS, HAPEX-Mobilhy, HAPEX-Sahel, LBA, etc., and coordinate with efforts of agencies involved in hydrologic remote sensing.

[59] A remote sensing observatory would allow us to assess more quantitatively the state-of-the-art on remote sensing and hydrologic prediction, thus providing a credible path toward future progress. Without being able to determine the uncertainty of many remote sensing products, it is hard to argue for resources needed for future progress. Since building observational systems is expensive, societal decisions leading to such investments need to be firmly based in science. The RSO will greatly improve our capability to make credible scientific recommendations of resource investments, including those directly affecting the research enterprise.